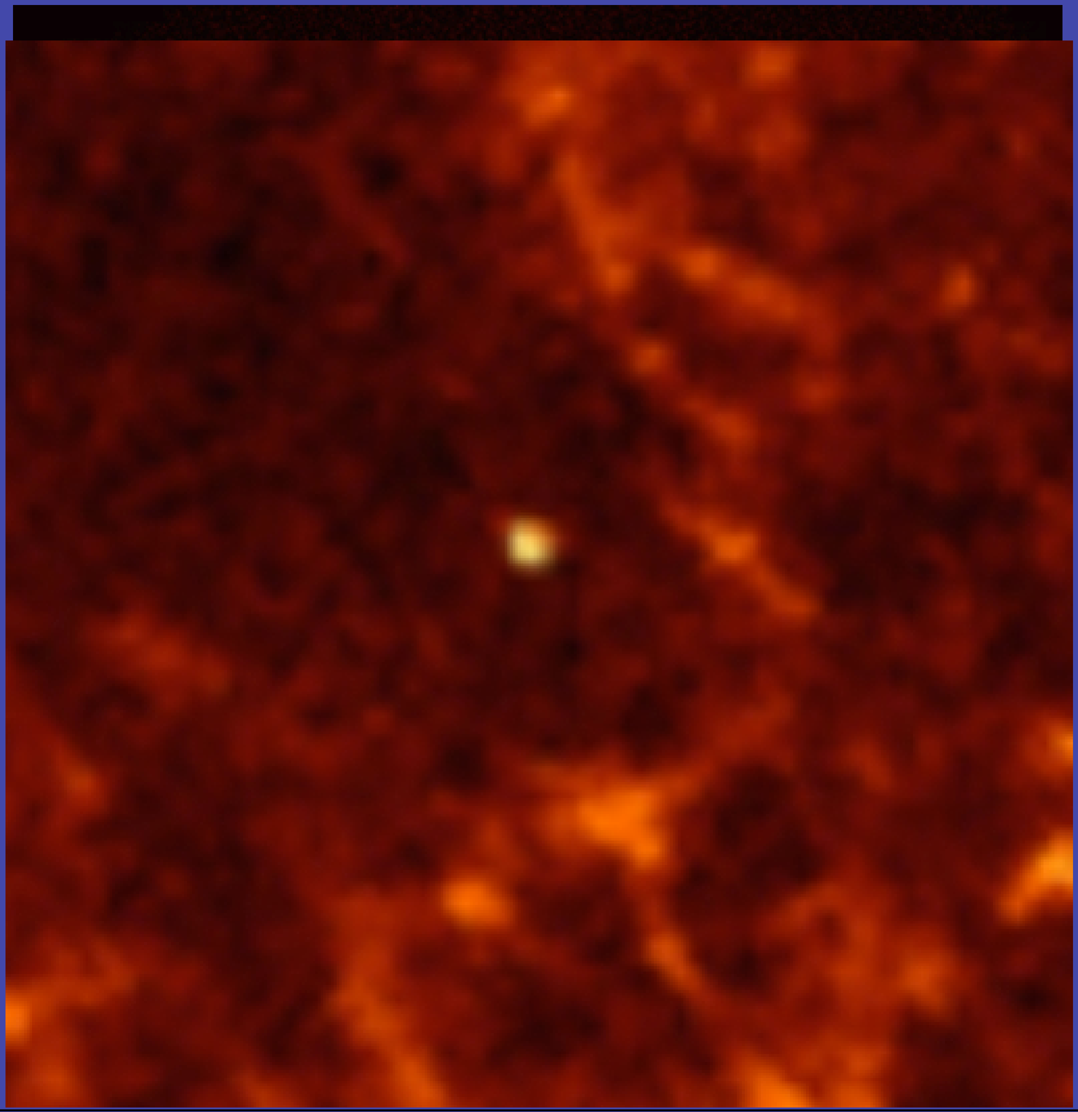
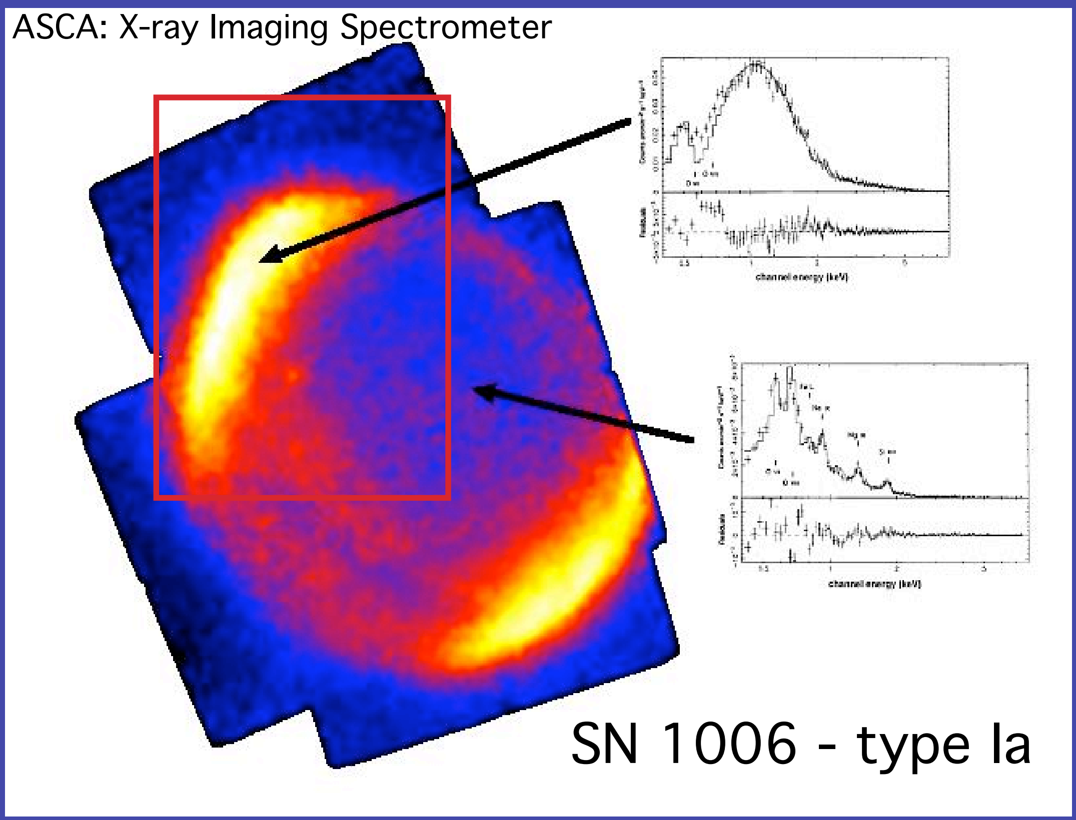
In The News ...

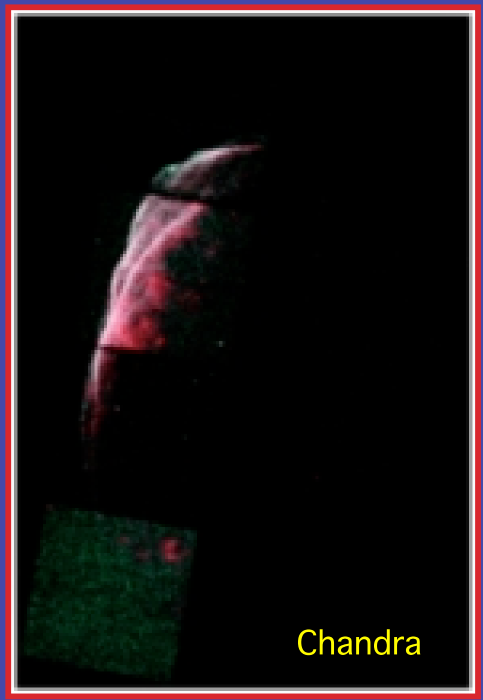


Chandra "first light" ACIS observation of the Cas A supernova remnant (thought to be the remains of a SNII). Chandra's unprecedented spatial resolution showed an X-ray bright point source near the center of the remnant.
A neutron star?

Acceleration Mechanisms

Supernova were long believed to be sources of cosmic rays (high energy subatomic particles distributed through the Galaxy). Spatially resolved X-ray spectroscopy helped prove this.



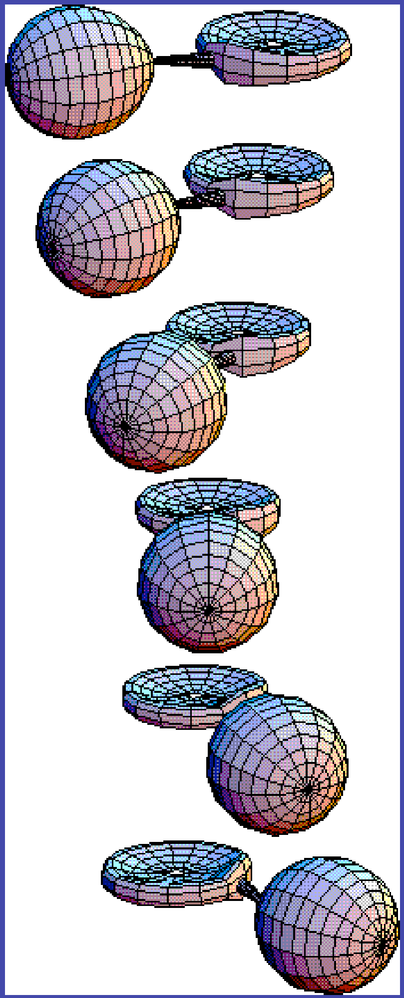


Explosions in Binaries: Novae

Semi-contact binary stars (one star fill its Roche Lobe and transfers mass to the companion) with a collapsed object (white dwarf or neutron star) as the non-contact component

Transferred material forms an accretion disk around the CO.

As material falls onto CO, it can radiate



Explosive Surface Fusion

- Material falling onto surface of the CO gets heated to extreme temperatures. Density and temperature of transferred material sufficient to allow H burning under explosive conditions (via CNO cycle in a C-O WD): a “classical nova”
- Star not destroyed.
- Novae can recur when a sufficient amount of matter transferred to the CO
- these “cataclysmic variables” are usually strong (transient) X-ray sources

Accreting White Dwarfs

White dwarfs can gain mass by RLOF from a companion star or (more slowly) from direct accretion from the ISM or direct accretion of the wind from a companion.

The "Chandrasekhar Limit" is the maximum mass that can be supported by electron degeneracy pressure and is

$$M_{ch} = 0.2\left(\frac{Z}{A}\right)^2\left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

$$M_{ch} = 1.4 M_{\odot}$$

(since Z/A =0.5)

What happens if a WD accretes enough matter that its mass is higher than M_{ch}?

SN Ia

SN Ia are believed involve the destruction of a WD either by:

- release of gravitational energy as the WD collapses to a NS as it exceeds the Chandrasekhar limit, or
- explosive thermonuclear fusion in a degenerate star (Hoyle & Fowler 1960)

Second mechanism is generally accepted explanation for SN Ia.

Reasons:

- Uniform lightcurve morphology powered by emission from decay of radioactive ^{56}Ni produced during the explosion
- no neutron stars for Galactic Type Ia’s (SN 1006, 1572, 1604)

Standard Candles

Major goal of astronomy is to identify objects of known (or standard) brightness so that distances can be measured via the inverse-square law.

SN Ia are used as "standard candles" since:

- they can be identified as discrete events (via lightcurve and spectral signatures)
- they have nearly all the same peak brightness: $M_B \approx M_V \approx -19.3 \pm 0.3$ with very small scatter
- because they are very luminous they can be seen to the edge of the Universe

Lightcurve Morphologies

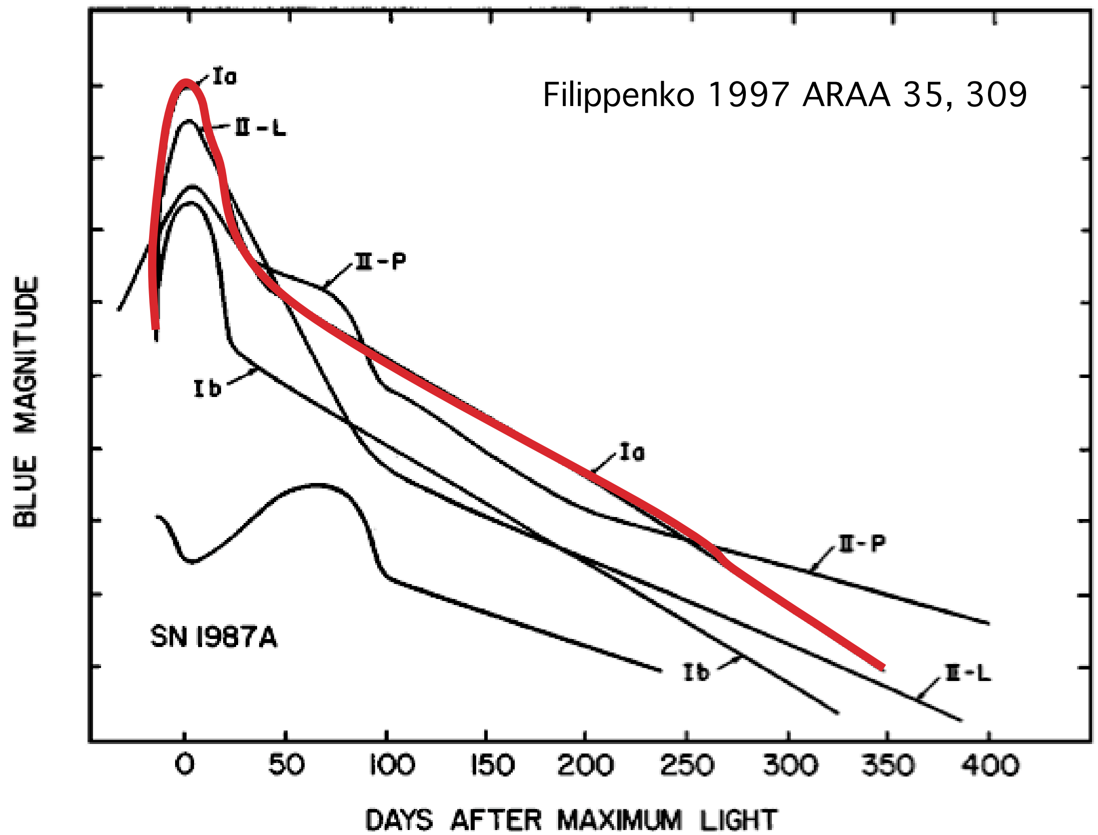


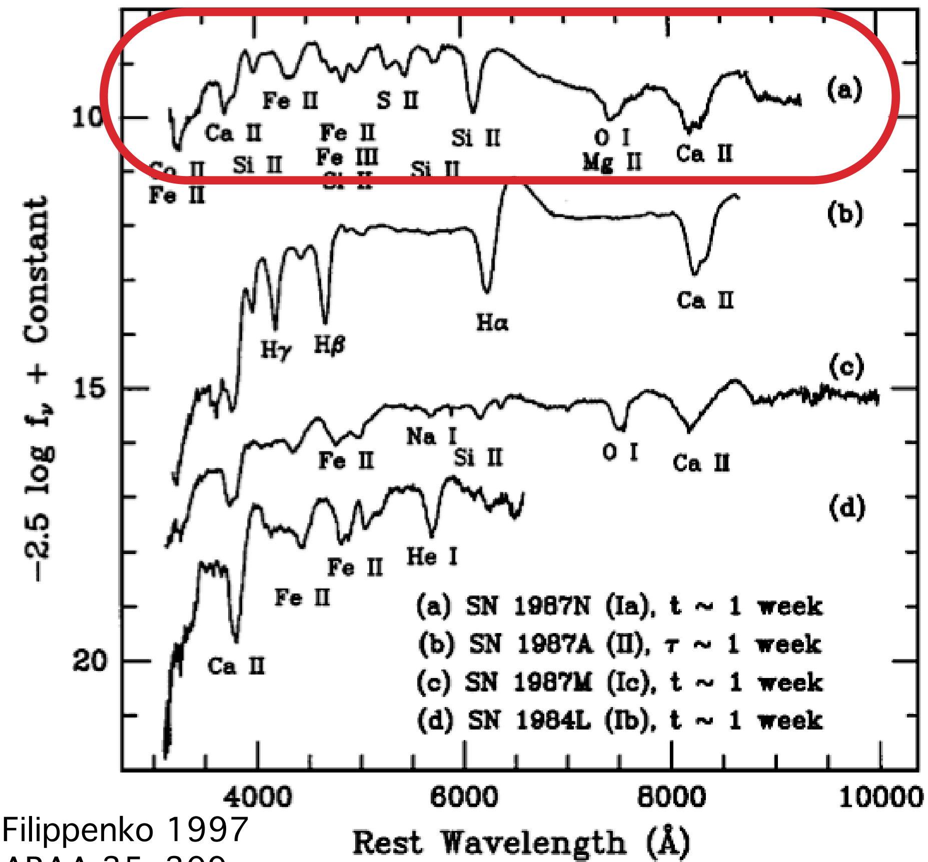
Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous. From Wheeler 1990; reproduced with permission.

Type I: all show similar lightcurves (similar precursors?) - rapid rise, short maximum, ~exponential decay

Type II: more varied; less luminous than Type I, longer rise, slower decay

Note: hard to catch SN prior to maximum light

Spectral Morphologies- Around Maximum Light



Filippenko 1997
ARAA 35, 309

Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables t and τ represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

Type I vs Type II: Type I shows no H lines; Type II shows strong H lines

Type I: progenitors are stars which have lost most of their H envelopes (WDs [Ia], WRs [Ibc])

Type II: progenitors still have most of their H envelope (RSGs, BSGs)

Summary:

Evolution of stars very important for understanding the evolution of the host galaxy and of the host universe

Detailed studies of supernova remnants allow direct tests of stellar evolution models and of models of envelope ejection

Outstanding questions:

- why did SN 1987a explode as a BSG instead of an RSG?
- How important are binaries?
- How “standard” are the SN Ia at high z?

The Active X-ray Sky

From the All-Sky monitor on the Rossi X-ray Timing Explorer

Neutron Stars and Black Holes

Neutron Star: object supported by pressure generated by degenerate baryons
Detected via periodic radio or X-ray emissions, or high X-ray luminosities
Typically $M<3M_O$, $R \sim 10$ km

Black Hole: a "Black Hole" is a region of space from which nothing can escape to infinity

Hard to detect directly

Characterized by the *Schwarzschild radius* R_s

$$R_s = \frac{2GM}{c^2}$$

or

$$R_s = 3\frac{M}{M_\odot}\ \mathrm{km}$$

If an object of mass M collapses to a size = R_s, then nothing can halt the collapse

Point of infinite density (singularity) may form

Rs also called the "Event Horizon"

Equations of States and Maximum Neutron Star Masses

There is no clear maximum mass for a neutron star as there is for white dwarfs, since the maximum mass of a neutron star is determined by details of the condensed baryon physics

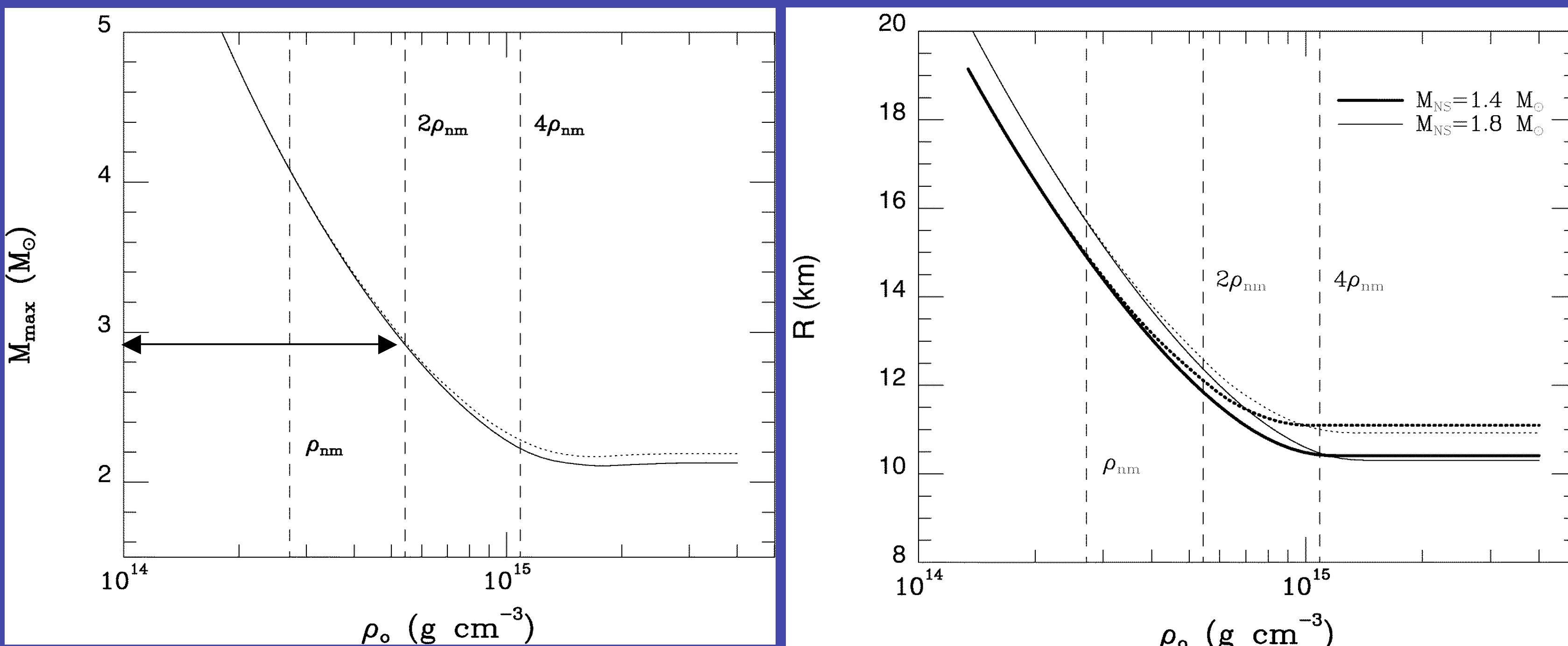
Behavior of baryons under degenerate conditions is complicated since baryons can decay into sub-particles at high densities

NS equations of state are complicated and poorly understood since our understanding of how matter behaves at such high densities is poorly understood

NS equation of state (pressure as a function of density) helps determine behavior of extremely condensed matter

Theoretical Limits for NSs

How Massive can a NS be?



Kalogera & Baym 1996

Implies a minimum value of the maximum NS mass ~ 3 M_O

Properties of Neutron Stars

Masses of single neutron stars not directly measurable

Information regarding masses of neutron stars best derived from observations of neutron star binaries

In many cases, LMXB/HMXB single-lined spectroscopic binaries (Doppler shift of the companion, star #2, is measurable only)

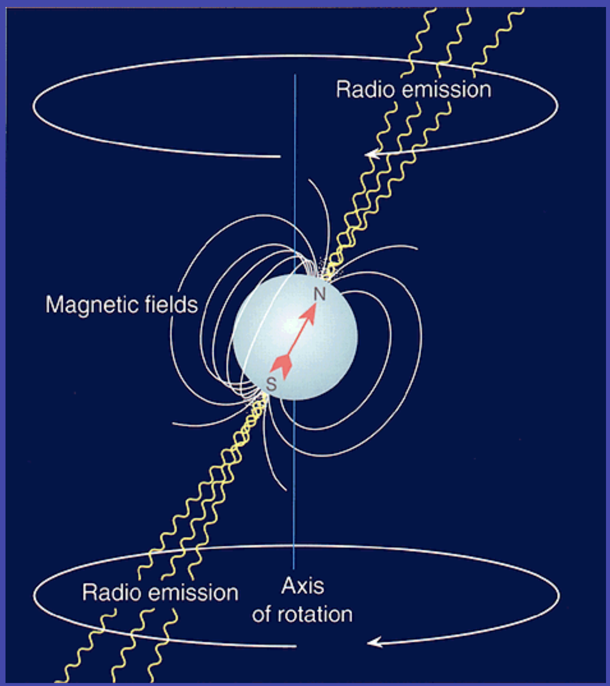
can construct the "mass function" *f(M)* as

$$f(M) = \frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \frac{P K_2^3}{2\pi G}$$

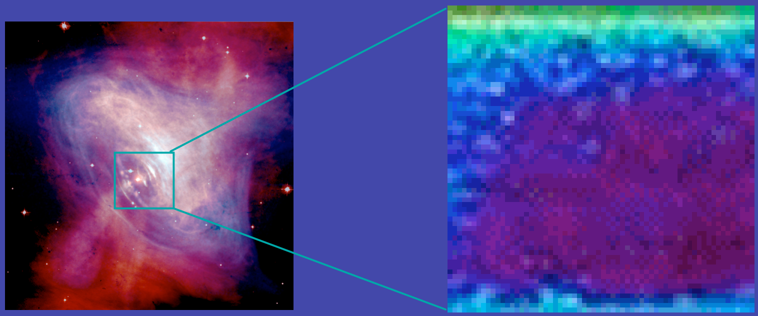
which is a lower limit ot the mass of the compact object (star #1)

Pulsars

Pulsars are neutron stars which emit periodic pulses of radio or X-ray emission (sometimes visible radiation as well)



http://nobelprize.org/physics/laureates/1993/illpres/magnetic.gif



http://www.ing.iac.es/~smt/WFS/pulsar.htm

Periodic emissions are doppler shifted as the neutron star orbits the companion

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{P - P_0}{P_0} = \frac{V}{c}$$

Masses of Pulsars in Eclipsing X-ray binaries

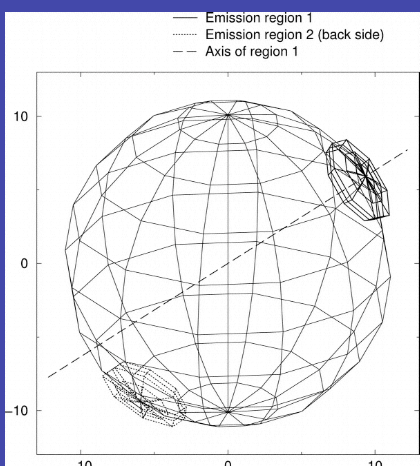
Table 1: Neutron Star Masses (Charles & Seward, Table 7.4)

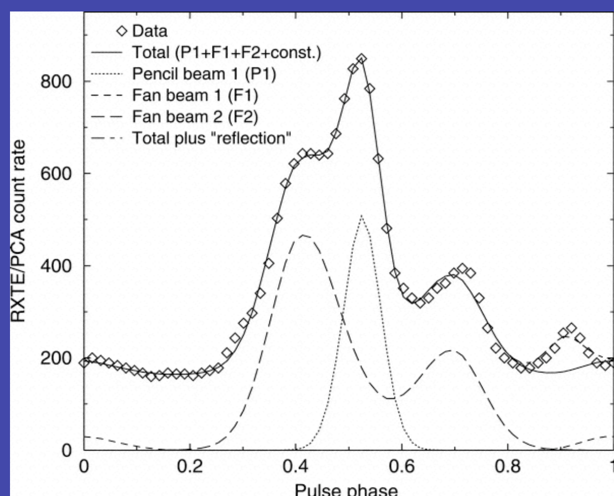
Source	Companion Mass ($M_\odot$)	Companion Radius ($R_\odot$)	i (degrees)	NS Mass ($M_\odot$)
Her X-1	1.99	3.86	80	0.98
SMC X-1	16.8	16.3	65	1.06
Cen X-3	19.8	12.2	75	1.06
LMC X-4	14.7	7.57	68	1.38
Vela X-1	23.0	34.0	83	1.77
4U1538-52	16.9	15.2	71	1.8

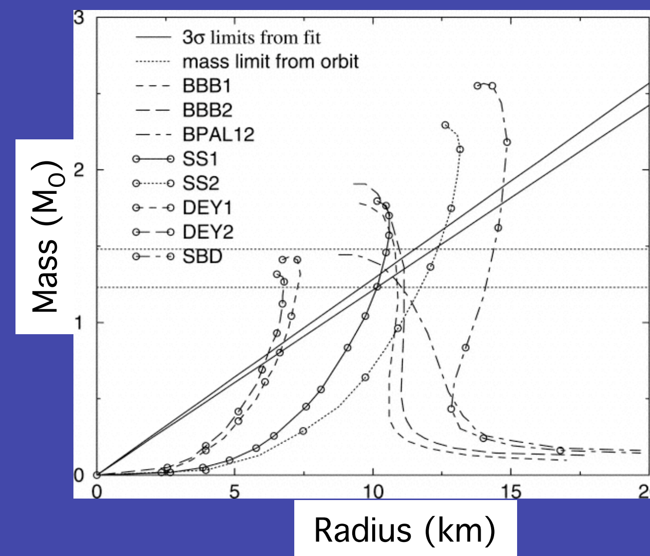
Constraining the NS Equation of State

Observations of X-ray pulsars have been used to constrain NS equations of states

Example: Her-X1: 1.24s pulsar in a 1.7 day orbit







The Size of Black Holes

The “size” of a black hole is proportional to its mass, and is given by the Schwarzschild Radius, $R_s = 3$ km (M/M_O)

Physically this means that as an object collapses to a size smaller than the Schwarzschild radius, the object can no longer communicate with the universe beyond this boundary.

Newtonian Derivation of R_s

Simple derivation of R_s: Consider a body of mass m escaping the gravitational pull of a body of mass M and radius R

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

if $v = c$ then

$$R_s = \frac{2GM}{c^2}$$

in some sense the Schwarzschild radius is the size of an object whose escape velocity equals the speed of light. Since nothing can go faster than light, nothing can escape from this object.

Useful but incorrect, since light not affected by Newtonian gravity.

Derived by Laplace (1795)

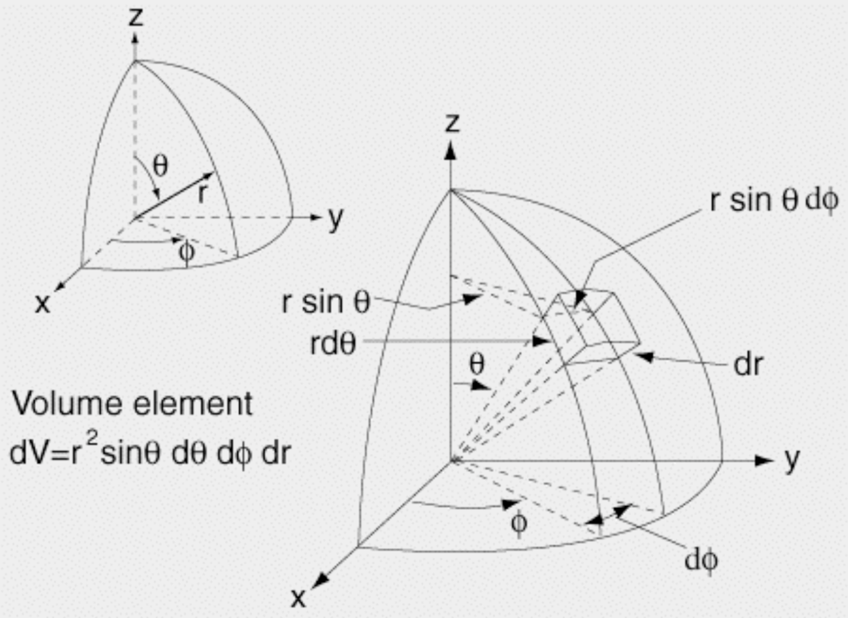
Euclidean Geometry

In Euclidean space, two points are separated by a length *ds* given by

$$ds^2 = dr^2 + r^2 d\Omega^2$$

where

$$d\Omega^2 = r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$



Relativistic Geometry

In General Relativistic spacetime, two points are separated by a length *ds* which is a function of position and time.

A particularly simple case is the “Schwarzschild metric”, describing the separation of 2 points in a spacetime which contains a single stationary object of mass M. In this case:

$$ds^2 = -(1 - \frac{2GM}{rc^2})(cdt)^2 + (1 - \frac{2GM}{rc^2})^{-1} dr^2 + r^2 d\Omega^2$$

Singular at $r=R_S=2GM/c^2$

At $r=1.5\ R_s$, photons will orbit the black hole: *photon sphere*

Time Dilation/Gravitational Redshift

For an observer at a constant position, their proper time is given by

$d\tau^2 = (1\text{-}2GM/rc^2)dt^2$

or

$$d\tau = \sqrt{1 - \frac{2GM}{rc^2}}dt$$

Thus for a clock in a gravitational field, time (dt) moves more slowly than for a clock at infinity ($d\tau$).

Since $dt = 2\pi/\nu, d\tau = 2\pi/\nu_0$, we have

$$\frac{\nu}{\nu_0} = \sqrt{1 - \frac{2GM}{rc^2}}$$

or

$$\lambda = \frac{\lambda_0}{\sqrt{1 - \frac{2GM}{rc^2}}}$$

since $\lambda_0 = c/\nu_0$ and $\lambda = c/\nu$.

Rotating Black Holes

Rotating Black Holes are described by the Kerr Metric (c=G=1)

$$ds^2 = -(1 - \frac{2Mr}{\Sigma})dt^2 - \frac{4aMr\sin^2\theta}{\Sigma}dtd\phi + \frac{\Sigma}{\Delta}dr^2$$
$$+\Sigma d\theta^2 + (r^2 + a^2 + \frac{2Mra^2\sin^2\theta}{\Sigma})\sin^2\theta d\phi^2$$
$$a = J/M, \Delta = r^2 - 2Mr + a^2, \Sigma = r^2 + a^2\cos^2\theta$$

There's a horizon at the vanishing of Δ, i.e. at $r^2 - 2Mr - a^2 = 0$

i.e. at $r_+ = M + \sqrt{M^2 - a^2}$

if a is not less than M: Naked Singularity?

Roger Penrose: Cosmic Censorship Conjecture

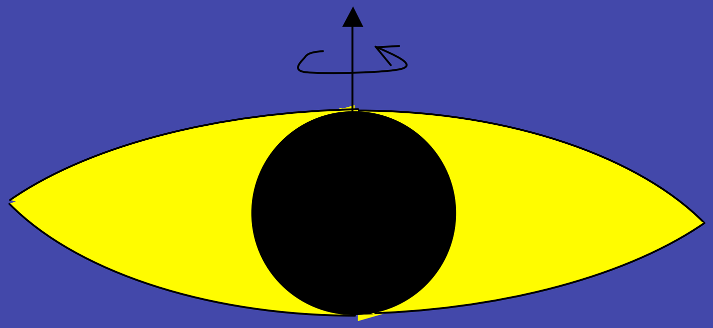
The Static Limit

For a rotating Black Hole, can show that there's a region of space around the horizon r_+ within which no static observer exists.

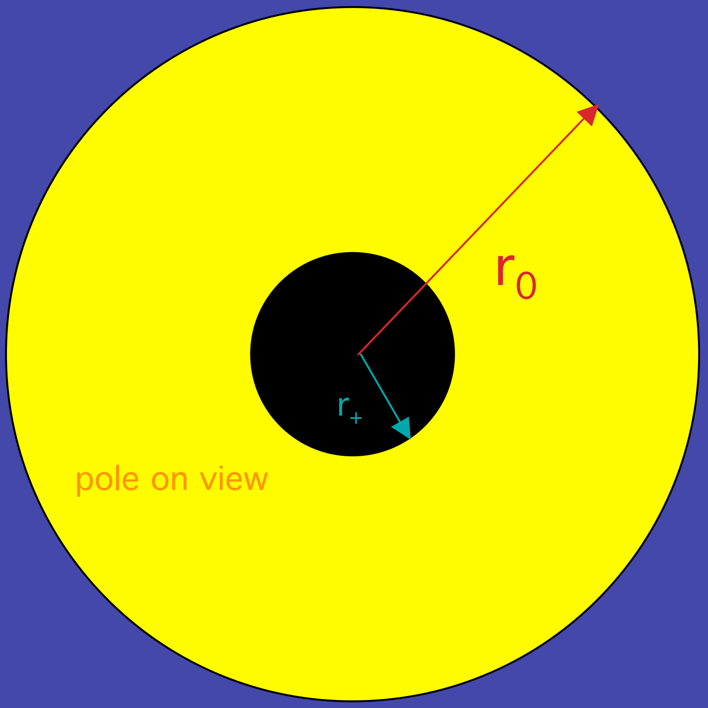
This static limit is given by:

$$r_0 = M + \sqrt{M^2 - a^2 \cos^2 \theta}$$

Thus, for $r_+ < r < r_0$, any object will rotate

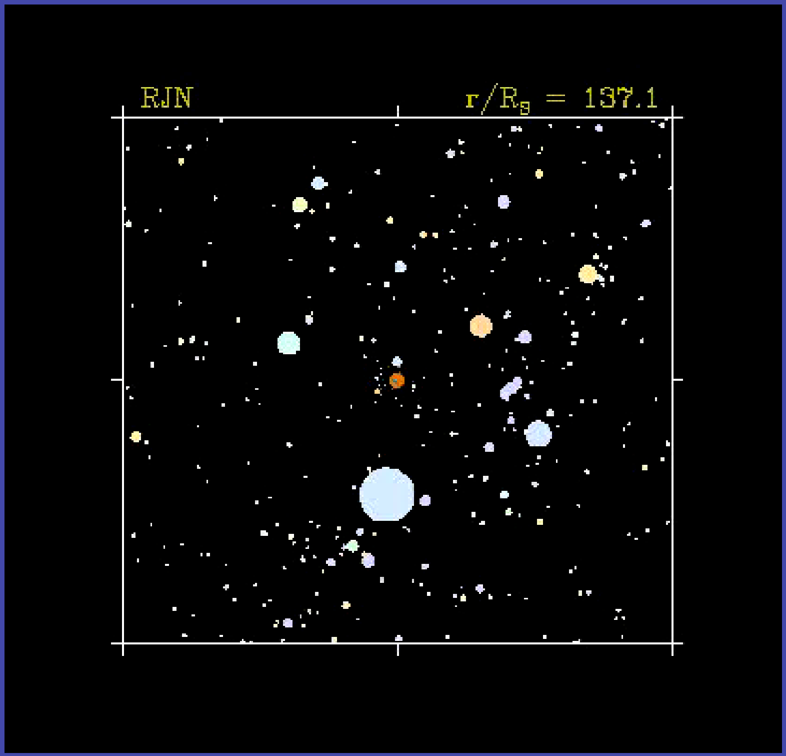


View normal to rotational pole

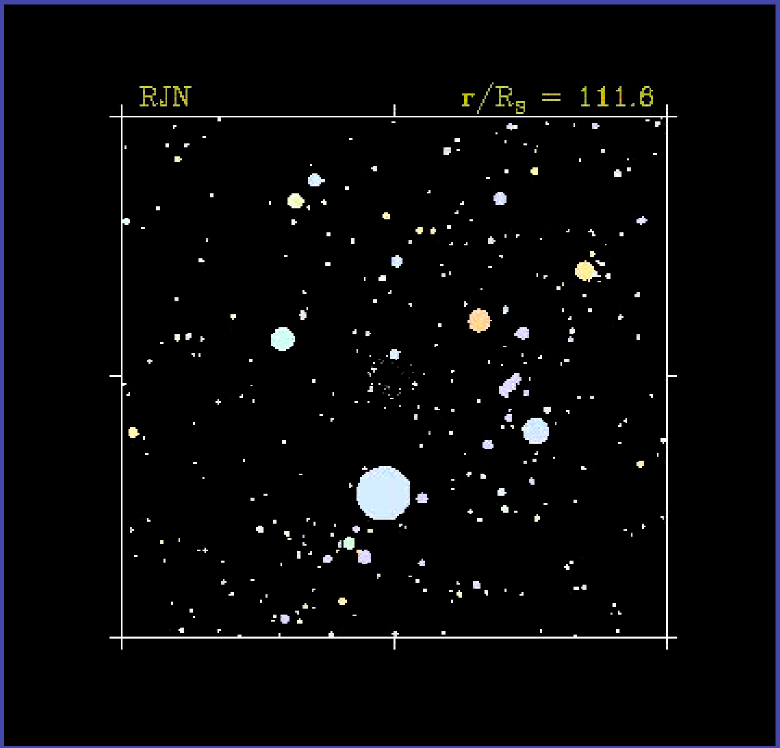


This region within the static limit (beyond r_+) is called the *ergosphere*

Approaching Compact Objects



Ultracompact NS

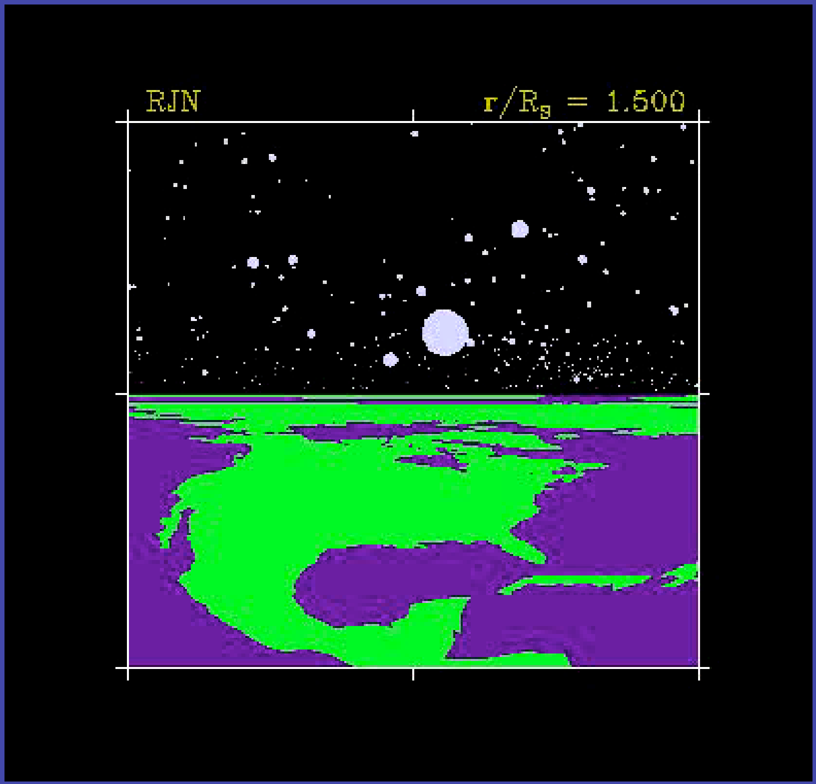


BH

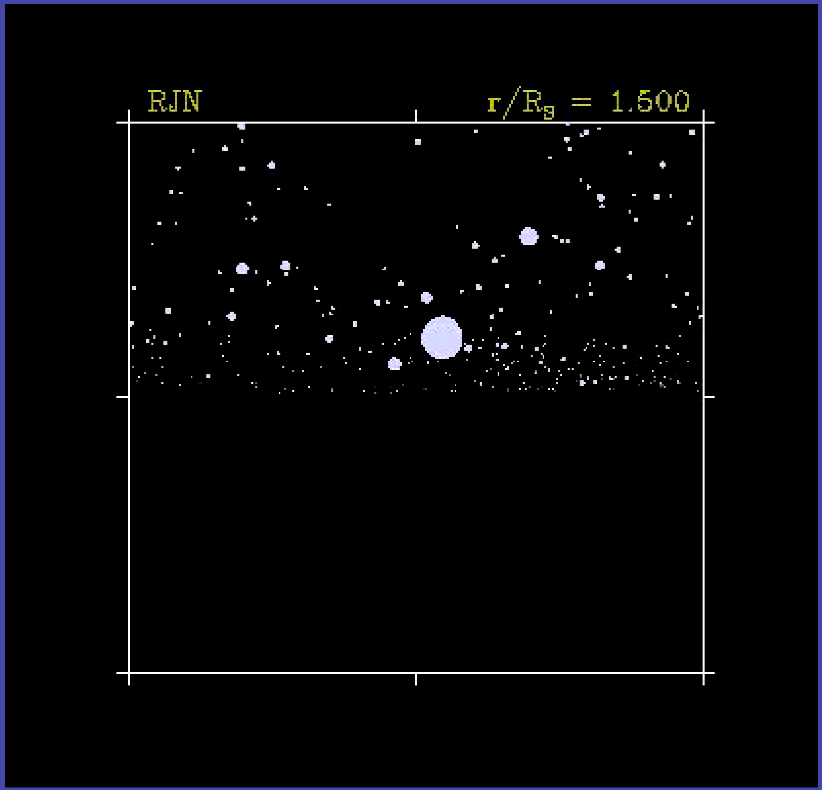
the following movies are from Bob Nemiroff's "Virtual Trips" page

http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html

Orbiting Compact Objects



Ultracompact NS



BH

Observer orbiting at the photon sphere

Hawking radiation

Black Holes have only 3 properties: mass, angular momentum and charge. Thus BHs represent a loss of information – or, an increase in entropy.

Jacob Bekenstein: BHs are thermodynamical objects and the entropy of a black hole is proportional to the surface area of the black hole.

Hawking: Black holes can radiate by swallowing virtual particles created from the quantum background

$$kT = \frac{hc^3}{16\pi^2 GM}$$

$$L = 4\pi R_s^2 \sigma T^4 = \frac{hc^6}{30720\pi^2 (GM)^2}$$

As black holes radiate, they lose mass, L increases, lose more mass...

Stellar Mass Black Holes: Formation

Stellar-mass black holes result from the final evolution of very massive stars

Mass of core plus overlying envelope may push core beyond limits where it can be supported by any type of force

Collapsars & Hypernovae

Extremely massive stars can produce a stellar core of mass in excess of 5 solar masses. It's believed that even neutron degeneracy pressure cannot sustain it

- direct collapse to a black hole ("collapsar")

Once believed to be underluminous SN, but now thought to be able to generate extremely bright SN due to direct accretion onto the black hole: "hypernovae"

Believed related to some types of Gamma-Ray Bursts

- appear extremely luminous in gamma-rays
- may be associated with massive star birthplaces.

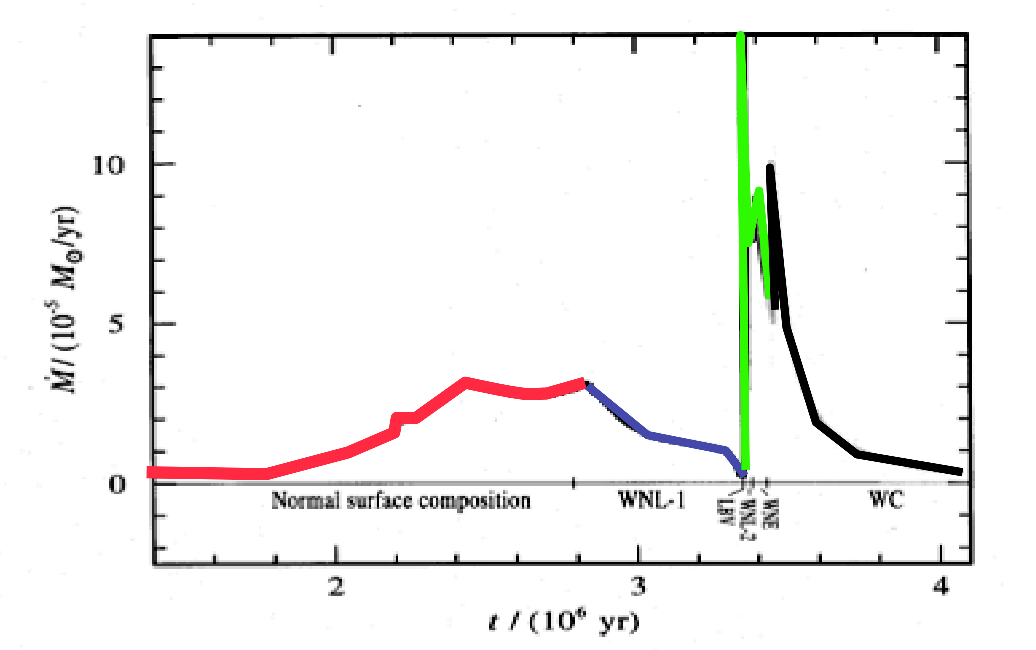
Collapsars & Mass Loss

Because massive stars lose mass as they die, the amount of mass loss during the star's life plays a critical role in what's left over.

A primary component of mass loss is the stars radiatively-driven stellar wind with mass loss rates of 10^{-6} to $>10^{-5}$ solar masses per year

Wind mass loss rate depends on metallicity since it depends on absorption of photons by atomic absorption lines

Mass Loss History



Langer et al. 1994

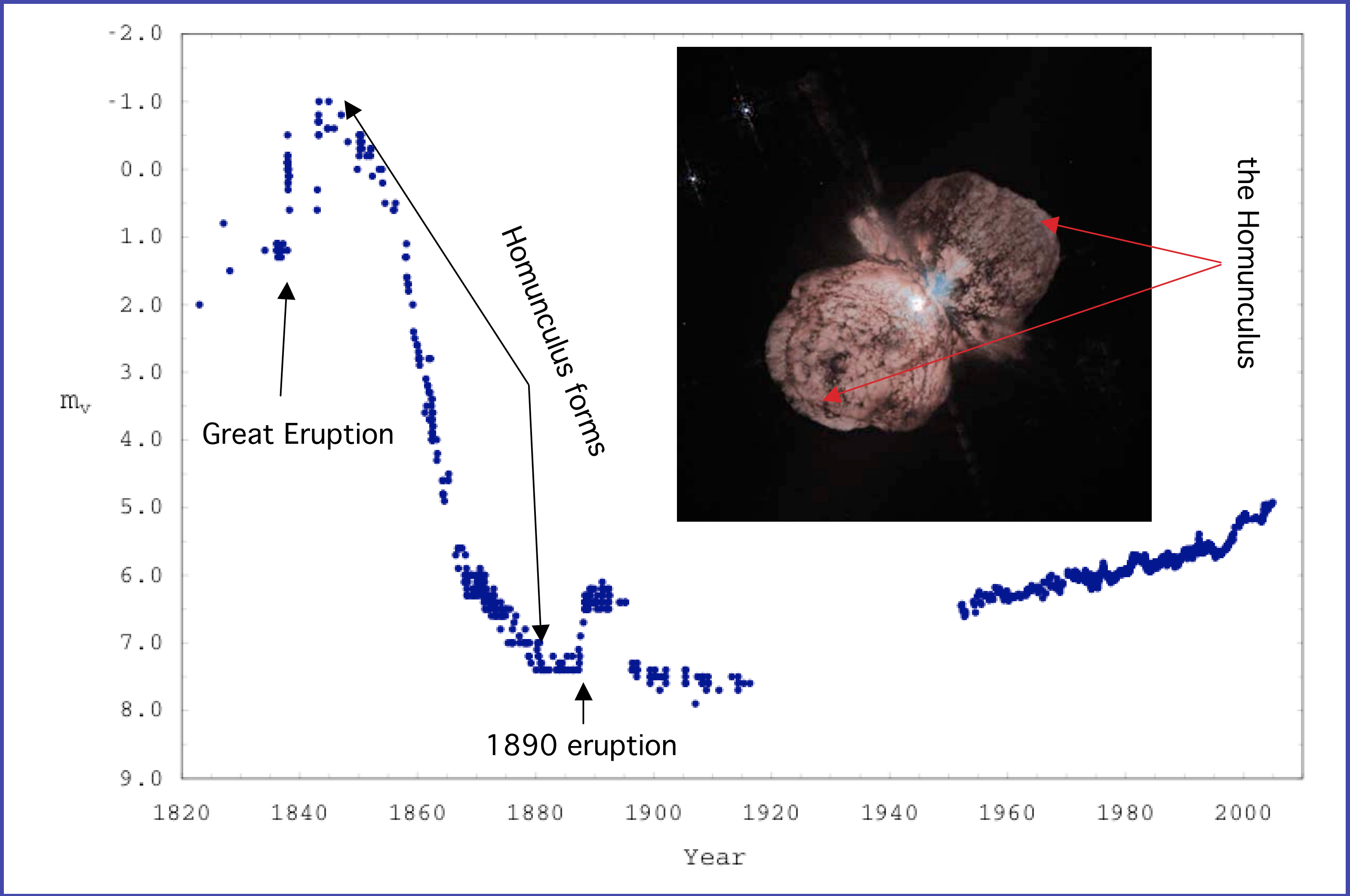
It comes down to the mass loss history - which is uncertain

Particular uncertainty: amount of mass lost in the "LBV" phase; or how many LBV eruptions a star can undergo

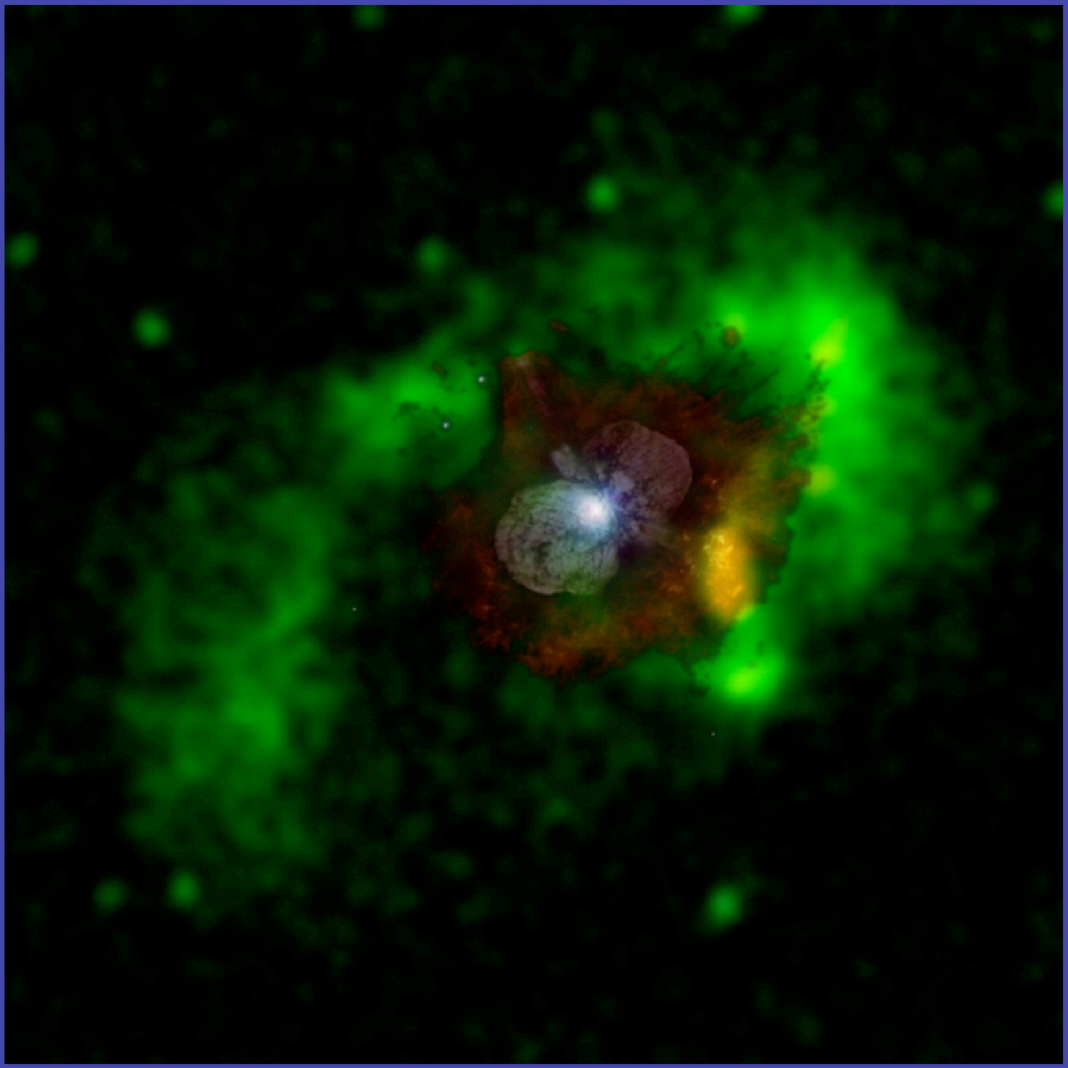
	M	log(t/yr)	M_{lost}	M_{end}
MS	60.0	6.5	17.6	42.4
WN	42.4	5.8	21.7	20.7
LBV	20.7	4.9	5.4	15.3
WNE/WC	15.3	5.8	11.4	3.9

SN Ib

Eta Car: A Multi-Ejection LBV



Eta Car: Imaging the Ejecta



During the “Great Eruption” the star ejected > 2 solar masses (best guess ~12 solar masses)

Optical and X-ray imaging show more distant ejecta: older eruption or faster, decelerated ejecta?

How often do such eruptions occur?

Fallback, Rotation and Jets

The amount of mass removed or left means that the SN explosion will have to be less or more powerful to remove the entire stellar envelope.

More mass loss: easier to remove envelope

Less mass loss: more massive envelopes, perhaps some of envelope falls back onto the core

CAVEAT: No two groups of supernova simulators presently agree on the final evolution of any star

Possibilities if lots of mass remains:

- mass falls back onto core to directly form a black hole (collapsar);
- rotation can provide enough angular momentum to produce an accretion disk and jet (jet-driven supernova)
- strong shock can propel most of the remnant outward, but some may fall back onto remnant of core over minutes to tens of hours, producing a black hole (fallback)

Importance of Mass Loss

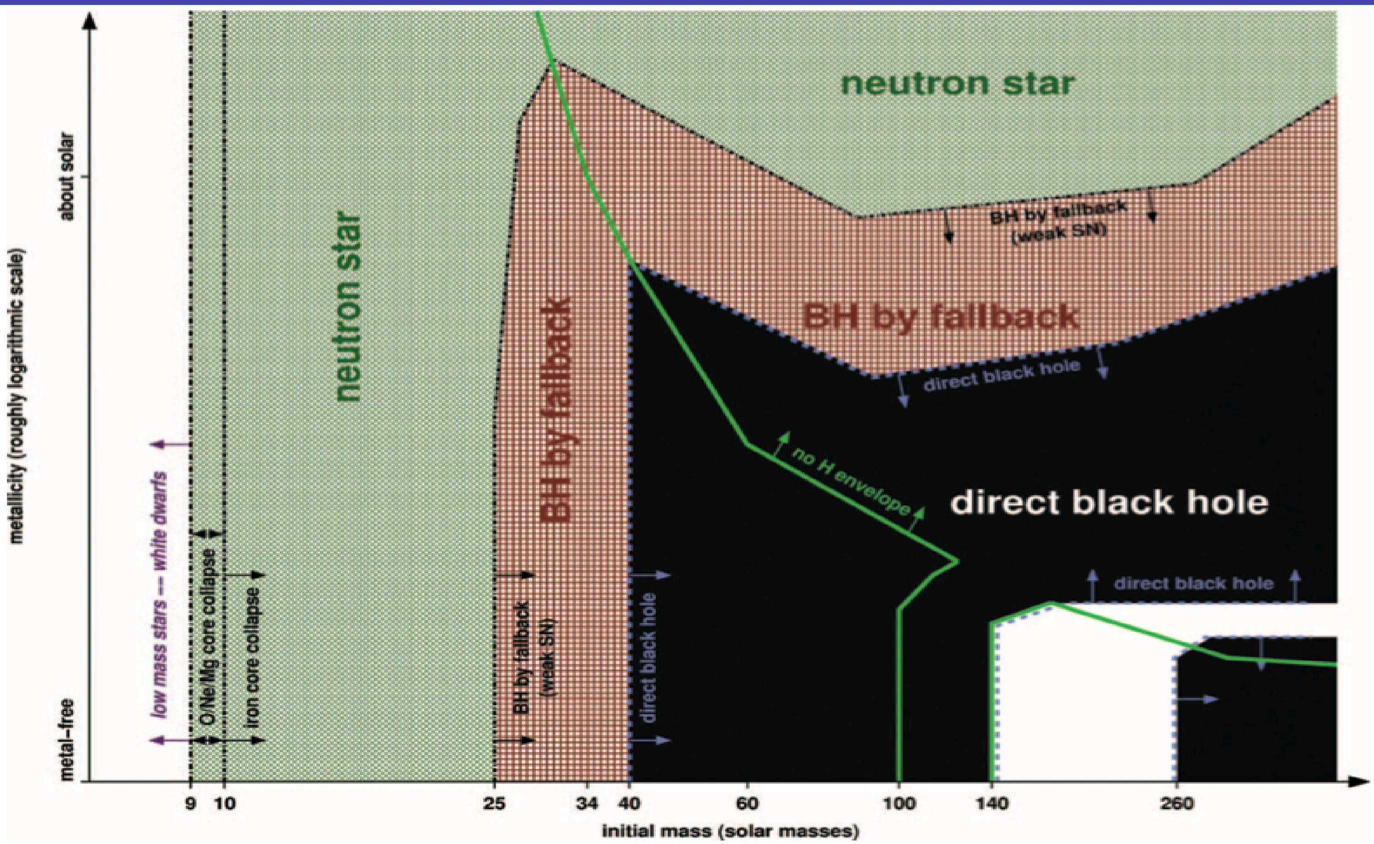


FIG. 1.—Remnants of massive single stars as a function of initial metallicity (*y-axis*; qualitatively) and initial mass (*x-axis*). The thick green line separates the regimes where the stars keep their hydrogen envelope (left and lower right) from those where the hydrogen envelope is lost (upper right and small strip at the bottom between 100 and 140 $M_\odot$). The dashed blue line indicates the border of the regime of direct black hole formation (*black*). This domain is interrupted by a strip of pair-instability supernovae that leave no remnant (*white*). Outside the direct black hole regime, at lower mass and higher metallicity, follows the regime of BH formation by fallback (*red cross-hatching and bordered by a black dot-dashed line*). Outside of this, green cross-hatching indicates the formation of neutron stars. The lowest mass neutron stars may be made by O/Ne/Mg core collapse instead of iron core collapse (*vertical dot-dashed lines at the left*). At even lower mass, the cores do not collapse and only white dwarfs are made (*white strip at the very left*).

Heger et al. 2003

Finding Black Holes

Properties of black holes difficult to constrain directly since by definition black holes (of reasonable sizes) do not radiate strongly.

but, Black Holes can be constrained by their gravitational interaction on their surrounds

One important type of interaction is the accretion of material and conversion of its gravitational potential energy to radiant energy.

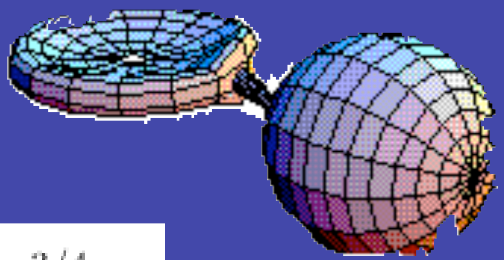
Accreting Sources

Accreting sources come in 2 flavors:

- Disk accretion in binaries (and around single supermassive black holes)
- Ambient accretion in binaries and single stars

Disk Accretion

Disk accreting systems consist of a compact object (often a NS) + non-degenerate companion; called LMXBs (low-mass X-ray binaries)



RLOF of the companion forms a hot disk around the CO

Disk temperature is

$$T = 2.3 \times 10^7 (\alpha \frac{M}{M_\odot})^{-1/4} [(\frac{M_\odot}{M})(\frac{R}{9 \text{ km}})]^{-3/4} \text{ K}$$

where α is an uncertain viscosity parameter; typical disks strong X-ray sources

Accretion disk surface brightness Q is

$$Q = \frac{3}{8\pi} \dot{M} \frac{GM}{R^3} (1 - \sqrt{\frac{R_o}{R}}) \text{ ergs cm}^{-2} \text{ s}^{-1}$$

where R_o is the innermost radius of the disk (Shakura & Sunyaev 1973)

Ambient Accretors

A CO can accrete from ambient material (ISM, stellar wind...)

HMXBs: CO (often a NS) + massive star (OB-type giant or supergiant) with a strong stellar wind

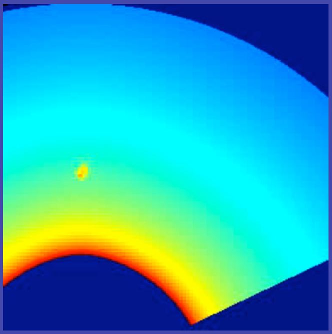
Accretion rate given by

$$\dot{M} = 4\pi(\frac{GM}{v_w^2})^2 m_p n_w v_w$$

Bondi & Hoyle 1944

The accretion luminosity *L* for an accreting body of mass *m* and radius *R* is

$$L \approx \frac{Gm\dot{M}}{R}$$



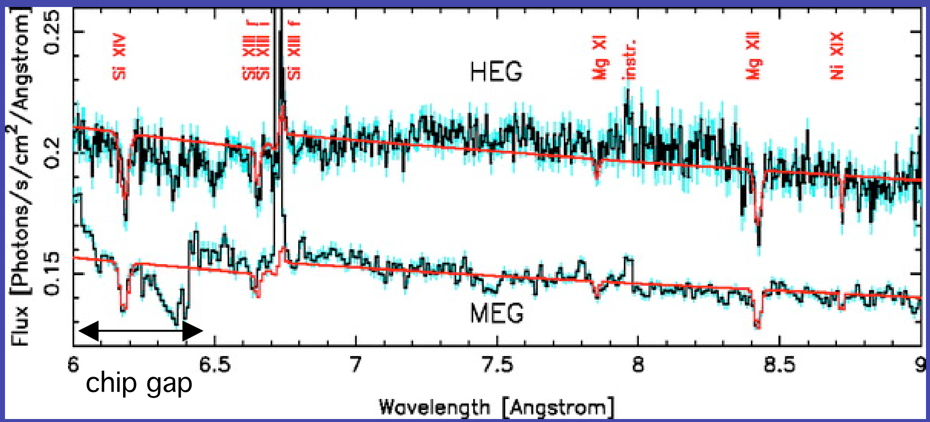
Because wind velocities are so high, temperatures usually kT>10 keV for HMXBs: X-ray sources

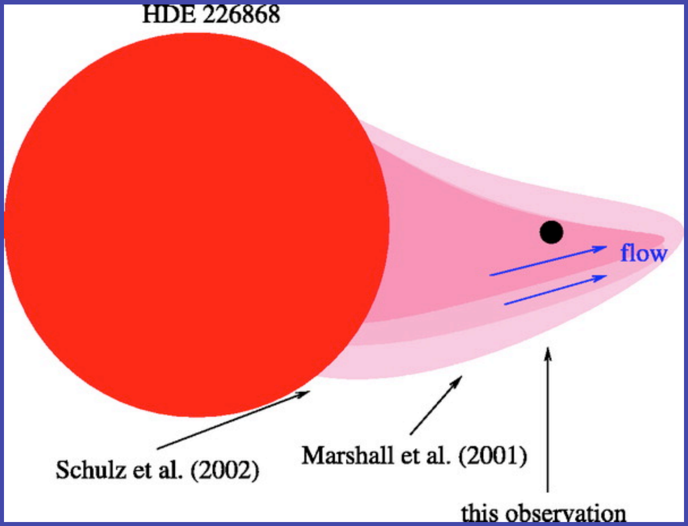
Accretion in Cyg X-1

Discovered in 1966 during an X-ray survey of the Cygnus region as a luminous, variable X-ray source. Identified in 1971with a supergiant star HDE226868 (O97Iab), which has a mass of $17M_O$

Inclination ~ 35°

Spectrometric analysis implies M_{CO}~10 M_O: a black hole





X-ray absorption lines produced off the orbital plane: a focussed wind?

Soft X-ray Transients & BHXRN

A particular class of accreting sources seem to have very unsteady accretion: very low accretion rates for long periods, then high accretion rates and outbursts for a short period of time.

Go from very faint to brightest objects in the sky at X-ray energies

Emission typically low energy (soft).

These systems (like V404 Cyg, A0620-00, and others) seem to contain black holes.

Sometimes called Black-Hole X-ray Novae (though brightening is different than in WD novae systems)

Old Faithful Black Hole Transient

Shows the ejection of the disk as a “jet” because of unstable accretion.

Measuring Masses of Stellar Black Holes

Masses of black holes in binaries can be constrained; unlike neutron stars, black holes (themselves) don't pulse (though their accretion disks may produce variable X-ray emissions)

Construct mass functions for single-lined binaries; look for large mass functions

Try to constrain mass of the companion spectroscopically to constrain mass of the compact object

$M_{CO} > M_{max,\ NS}$ => Black Hole

Masses of Stellar Black Hole Candidates

Binary	Likely $M_X (M_\odot)$	$f(M)=M_{X,min} (M_\odot)$
4U1543-47	5 ± 2.5	0.22 ± 0.02
GRO J0422+32	10 ± 5	1.21 ± 0.06
GRO J1655-40	7 ± 1	2.73 ± 0.09
SAX J1819.3-2525	10.2 ± 1.5	2.74 ± 0.12
A0620-00	10 ± 5	2.91 ± 0.08
GRS 1124-683	7 ± 3	3.01 ± 0.15
GRS 1009-45	4.2 ± 0.6	3.17 ± 0.12
H1705-250	4.9 ± 1.3	4.86 ± 0.13
GS 2000+250	10 ± 4	4.97 ± 0.10
XTE J1118+480	7 ± 1	6.0 ± 0.3
GS 2023+338	12 ± 2	6.08 ± 0.06
XTE J1550-564	10.5 ± 1	6.86 ± 0.71
XTE J1859+226	10 ± 3	7.4 ± 1.1
GRS 1915+105	14 ± 4	9.5 ± 3.0

http://cgpg.gravity.psu.edu/events/conferences/Gravitation_Decennial/Proceedings/Plenaries/Sunday/Narayan/narayan_plenary.pdf

Measuring the Spin of a Black Hole

For a black hole material outside event horizon up to some limit can orbit stably around the black hole.
This limit called the Innermost Stable Circular Orbit, r_{ISCO}

$$
\begin{aligned}
r_{ISCO} &= M(3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2} \\
Z_1 &= 1 + (1 - a^{2/M^2})^{1/3}[(1 + a/M)^{1/3} + (1 - a/M)^{1/3}] \\
Z_2 &= (3a^2/M^2 + Z_1^2)^{1/2}
\end{aligned}
$$

In the Kerr Metric,

$$\Omega = \pm \frac{\sqrt{M}}{r^{3/2} \pm aM^{1/2}}$$

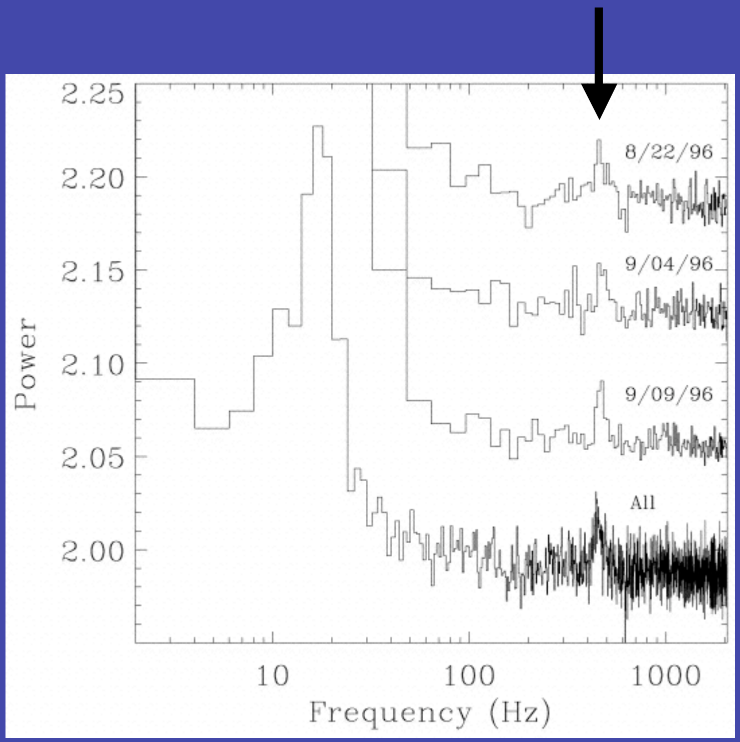
(Shapiro & Teukolsky 12.7.19)

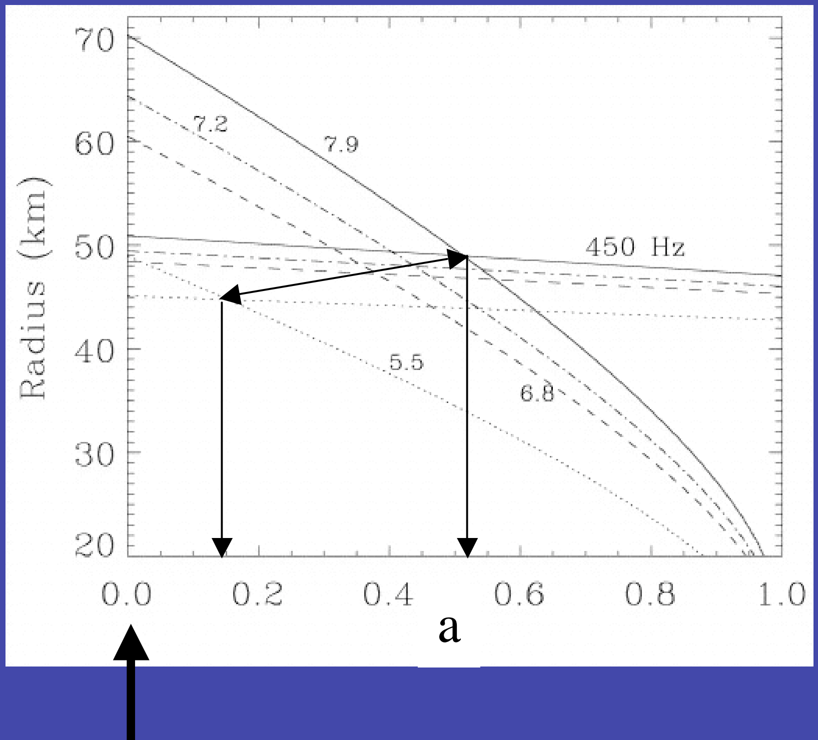
So the highest periodic signal from a BH can occur near r_{ISCO}; measure M_{BH}, then can deduce *a*, the specific angular momentum of the BH

Example: GRO J1655-40 (Nova Sco 1994)

$5.5M_O < M_{BH} < 7.9\ M_O$

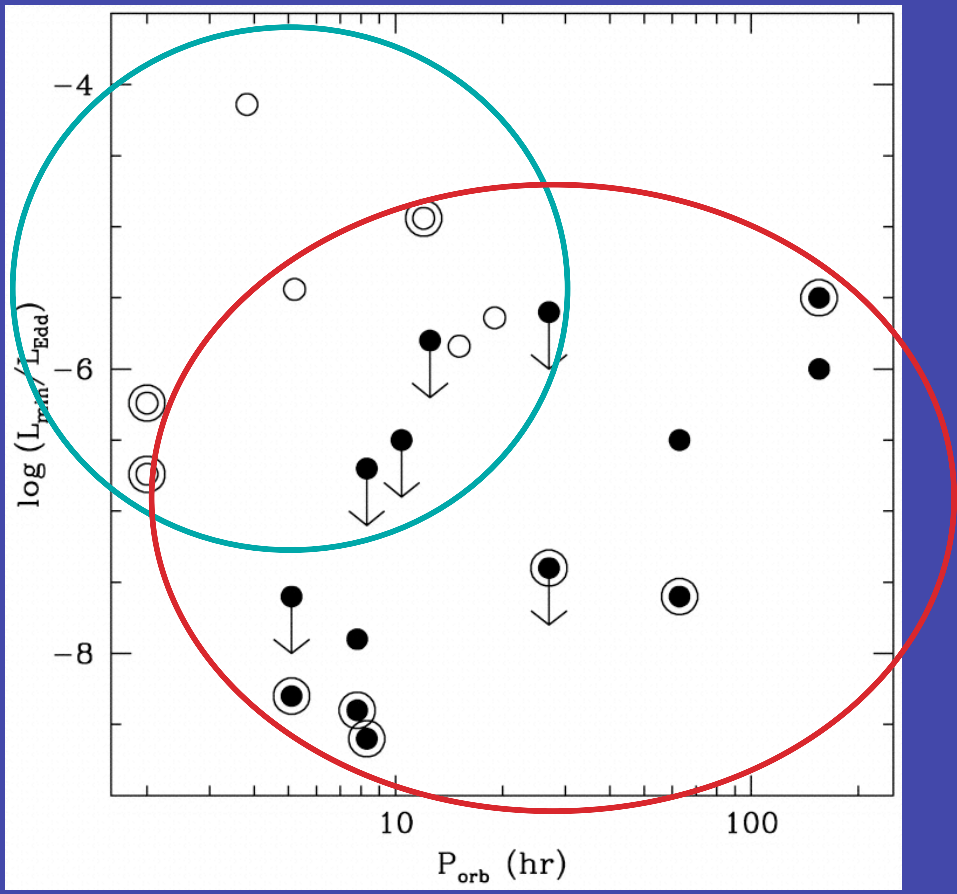
This X-ray binary was observed with RXTE and found to have a “quasi-periodic oscillation” with a frequency of 450 kHz





a=0: ruled out

Event Horizons found?



Quiescent luminosities of BHXNs (filled circles) and NSXNs (open circles) from Garcia et al. 2001

X-ray luminosity of X-ray Novae containing neutron stars in quiescence were compared to X-ray luminosity of XRNs containing BHs.

- BH systems were subluminous compared to NS systems.
- BHs hide some of their accretion luminosity behind the event horizon?

ULXs

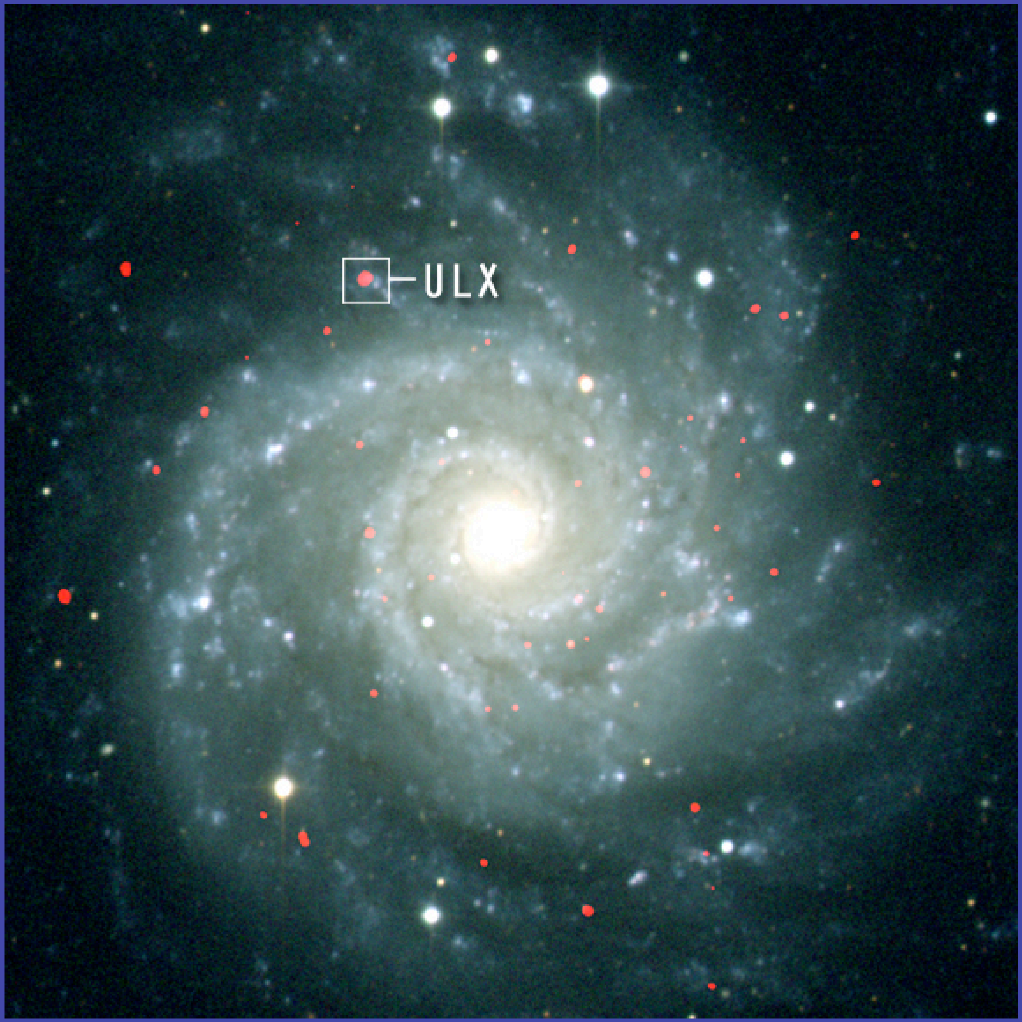
Eddington Limit: Luminosity of an object when its radiation pressure force on electrons equals the force of its self gravity

$$L_E = 4\pi G M m_p c/\sigma_T = 1.2 \times 10^{38} (\frac{M}{M_\odot}) \text{ ergs s}^{-1}$$

ULXs= ultraluminous X-ray sources: compact, off-nuclear X-ray sources with X-ray luminosities in the range of $L_x \sim 10^{39}$ - 10^{41} erg/s, i.e. 10-1000 L_E

About 200 ULXs are known

ULX example: M74



CHANDRA/ACIS sources in red (J.Liu et al. & T.Boroson)

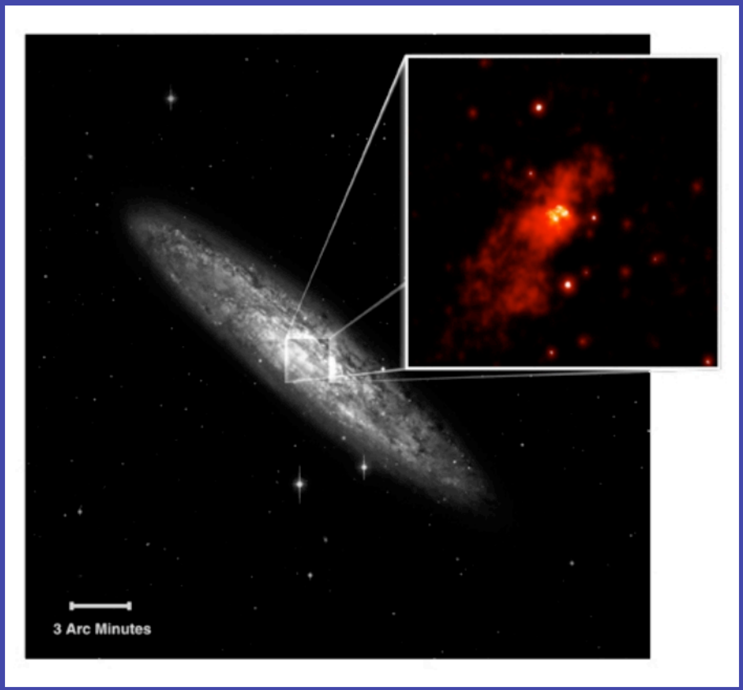
ULX in M74
Quasi-period of 2 hours
100 M_O Black Hole?
(probably not an unresolved group of LMXBs)

Intermediate Mass Black Holes

How can BHs with $M > 100\ M_\odot$ form?

too large for normal stellar evolution (with $Z>0$) since $M_{star}<150\ M_\odot$ (Figer 2005)

Collision of many stellar mass BHs in massive star cluster?

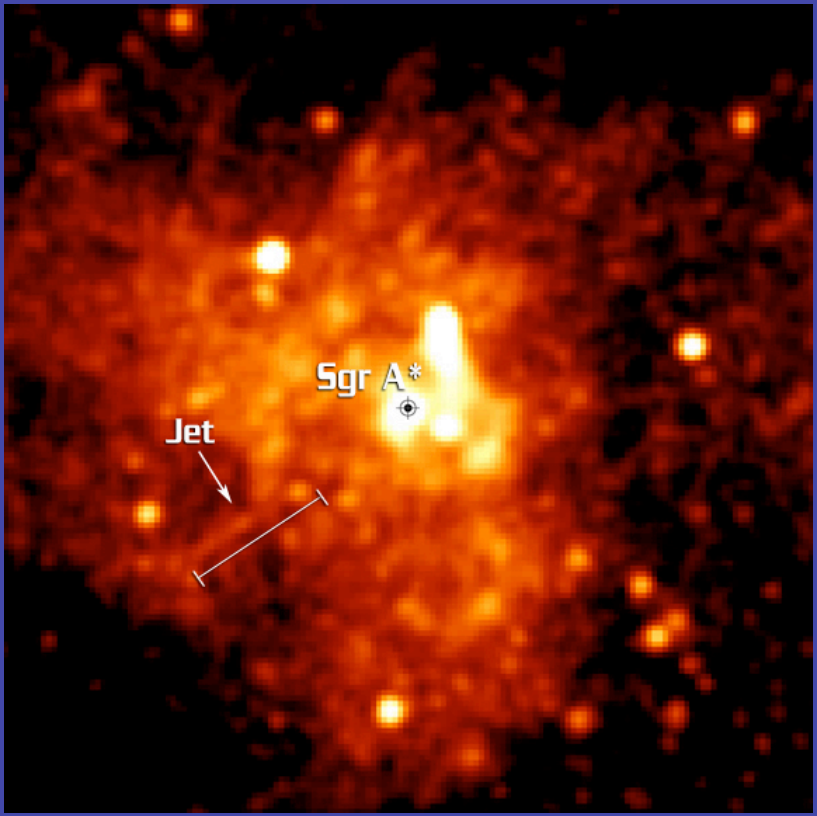


NGC 253

A "starburst" galaxy with 6 ULXs near the center of the galaxy

Supermassive Black Holes

Centers of some types of galaxies seem to house supermassive ($M \sim 10^6\ M_\odot$) black holes

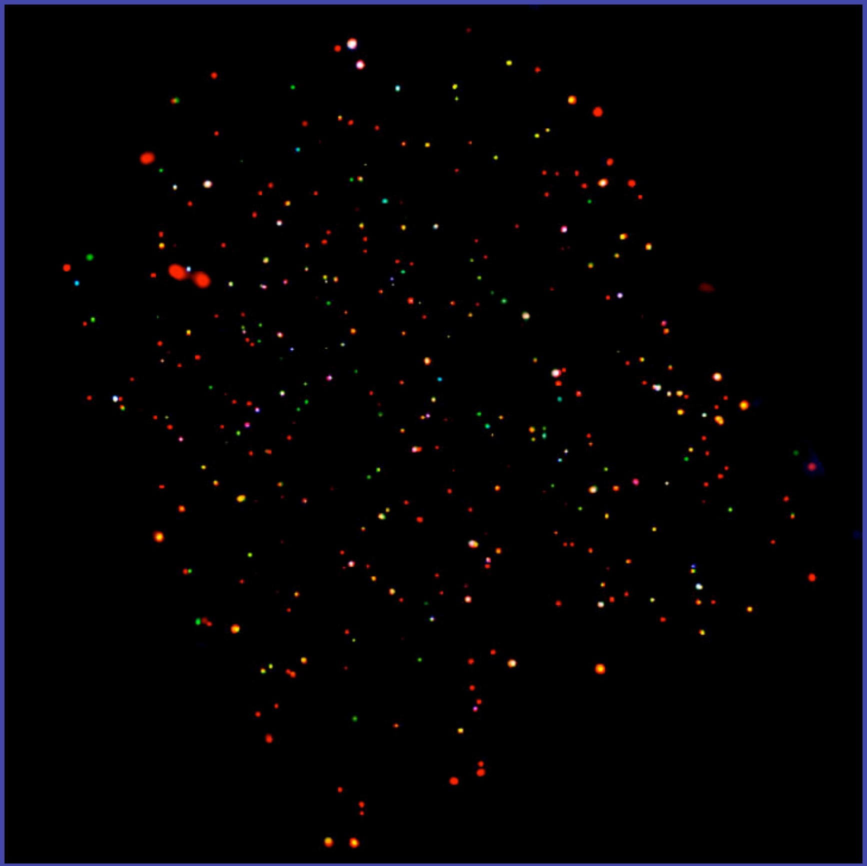


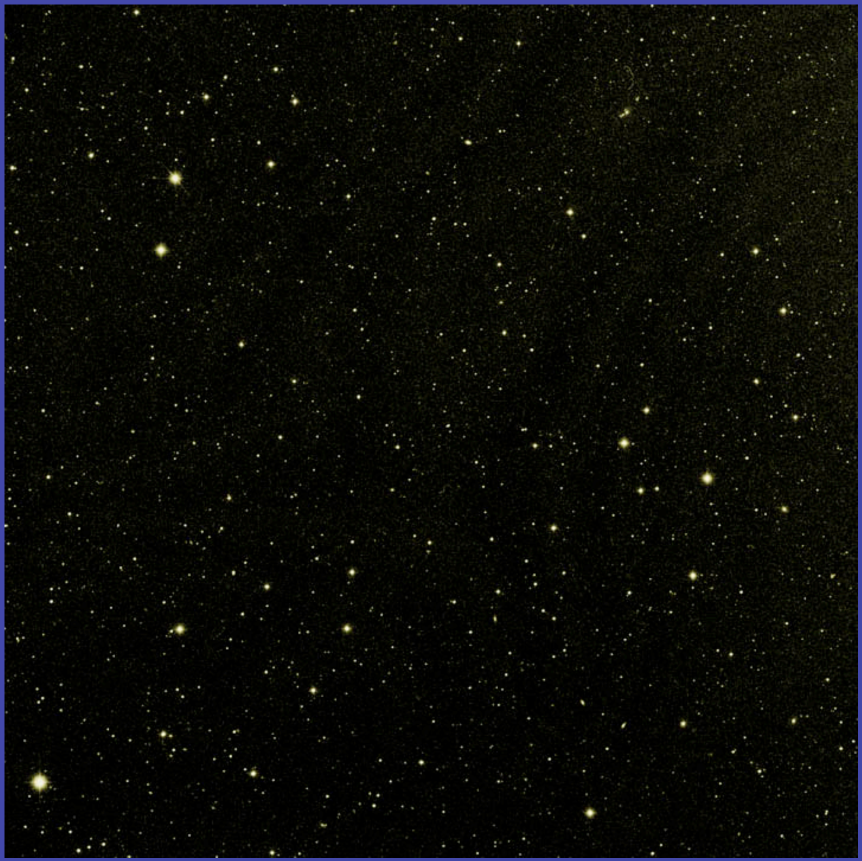
Sgr A* is the Milky Way's supermassive black hole

In the current epoch most SMBHs have low L_x's.

At high redshifts, SMBHs have very large L_x's - dominate bolometric luminosity

SMBH Census





Chandra observations of the "Lockman Hole" (a region of very low Galactic absorption) detects a large number of SMBHs. Found:

- BH activity peaked 6 billion years ago
- Smaller black holes turned on later

Summary

Population of compact objects in our galaxy very uncertain: how many faint ones are there?

COs are prime labs for extremes of physical study (esp. GR, condensed matter)

Most NSs seem to have masses much lower than the upper limit of about 3 Msuns

Black holes can have any mass: lowest mass is about 5 solar masses (no mini-black holes yet)

How do intermediate mass black holes form, if they exist